

# Theory Summary

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## Abstract

In this review, I show a personal overview of theoretical results shown in the International Conference on the Initial Stages in High-Energy Nuclear Collision, in Illa da Toxa, Galicia, Spain, Sept. 8-14, 2013.

*Keywords:* high energy nuclear collisions, quark gluon plasma, initial stage

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## 1. Introduction

There are 25 plenary and 33 parallel theory talks in the International Conference on the Initial Stages of High-Energy Nuclear Collisions (IS2013), so I must be very selective and summarize them only from a personal point of view. Therefore readers are advised to browse slides of the talks which can be found in the website of the conference [1] together with these proceedings.

Before going to details about each topic, I show two theoretical results which led to motivation for holding this conference. According to the local organizers, the aim of the conference is to set a framework of cross-talk among researchers who conduct a research on initial stages of high energy nuclear collisions *and* on final hydrodynamic evolutions along with other topics such as nuclear parton distribution function and thermalization just after collisions: The name of the conference apparently indicates topics covering only the former, which is not actually true. All topics shown in Fig. 1 are intimately related with each other: Final observables to be compared with experimental data originate from convolution of them.

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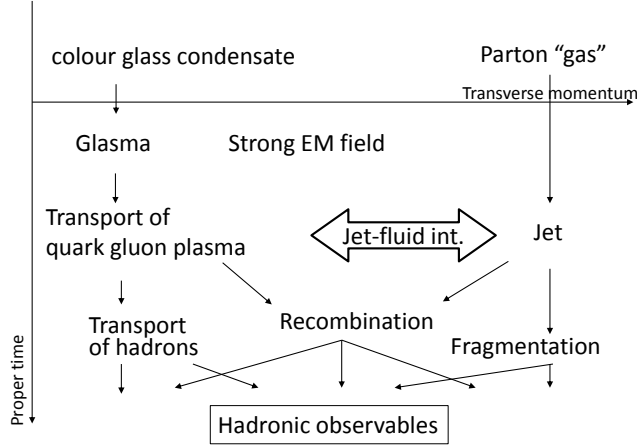


Figure 1: Topics of this conference and their mutual relations.

An announcement of discovery of perfect fluidity was made in 2005 [2]. This is based on a fact that elliptic flow parameters  $v_2$  are reproduced remarkably well from ideal hydrodynamic calculations with Glauber type initial conditions [3, 4, 5, 6, 7]. Just after that, it was claimed ideal hydrodynamics with color glass condensate (CGC) initial condition does not reproduce  $v_2$  data [8] as shown in Fig. 2. It is well known that  $v_2$  is almost proportional to initial eccentricity of the profile just after collisions. So the discrepancy between the data and the model calculations comes mainly from larger initial eccentricity from the CGC model than that from the Glauber model. For many years, understanding of initial conditions in hydrodynamic models had been very important. Nevertheless, after this work, importance of discrimination of initial models was recognized again more than ever. Nowadays it becomes a standard scheme to analyze the data by comparison of hydrodynamic results from several initial conditions such as Glauber and CGC with each other

Before  $\sim 2007$ , most of hydro groups except for Rio de Janeiro-Sao Paulo group [9, 10, 11] employed smooth initial conditions which could be identified

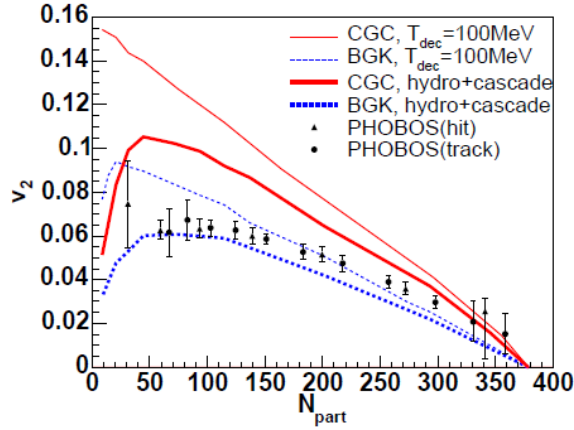


Figure 2: Integrated elliptic flow parameter  $v_2$  at midrapidity as a function of the number of participants [8]. Red (Blue) solid line is the result from a hybrid model with CGC (Glauber) initial condition. Dashed lines correspond to the results by assuming kinetic freezeout happens at  $T = 100$  MeV.

with event-averaged initial conditions. However, event-by-event fluctuation in the initial conditions turned out to be important after the third order deformation parameter resolves the ridge and Mach cone problems simultaneously [12]. Figure 3 shows position of participants and spectators from the PHOBOS Monte-Carlo Glauber model. In this particular event, a profile of participants looks like a triangular shape. The system responds to this initial profile and in particular in central events the signal of triangular flow  $v_3$  becomes comparable with that of elliptic flow. Odd harmonics has never been considered seriously until then.

These two results opened up a new era of investigating details of initial conditions and triggered quite a lot of work on initial stages thereafter. I think this is a part of the main reasons why this conference was held.

Along the lines of the thought, I highlight the topics of p/d-A collisions, isotropization, thermalization, fluctuations and recent development in hydrodynamics and transport theory in this review.

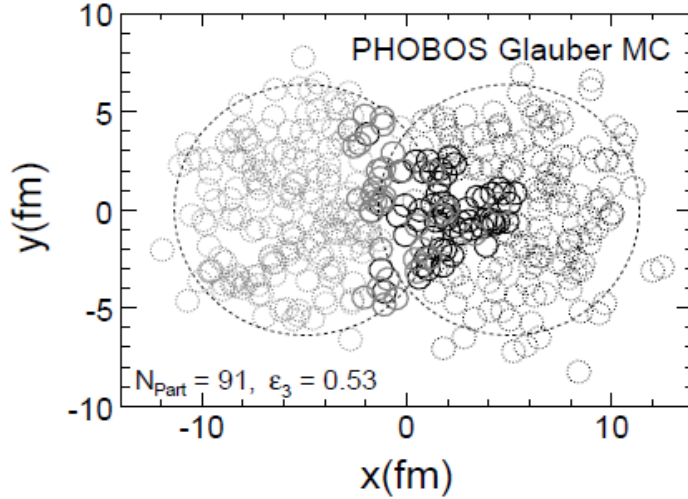


Figure 3: An sample of event in the transverse plane from the PHOBOS Monte-Carlo Glauber model [12].

## 2. p/d-A collisions

One of the big surprises in the physics of high-energy nuclear collisions is apparent collectivity of matter created in p/d-A collisions. p/d-A collisions were called “control experiment” to understand the so-called cold nuclear matter effects such as Cronin effect, nuclear parton distribution and so on. Basic consensus in the community was that no quark gluon plasma (QGP) is created in such collisions due to its smallness. However, recent experimental data show ridge structure in p-p [13] and p-A collisions [14, 15] at LHC and finite  $v_2$  in d-A collisions at RHIC [16].

The ridge structure in p-A collisions at the LHC energy can be understood as an initial state effect within the CGC picture qualitatively [17]. However, what is more surprising to us is mass ordering behavior, which has been a strong signal of collectivity in A-A collisions, is observed even in p-A collisions at LHC [15] and in d-A collisions at RHIC [16]. Mean transverse momentum as a function of multiplicity for particle identified hadrons such as pions, kaons and protons are

well separated [18], which indicates existence of radial flow. Furthermore mass ordering pattern of  $p_T$  differential elliptic flow  $v_2(p_T)$  [19] also indicates final rescatterings effects. These observables are reasonably reproduced by employing a hydrodynamic model [20]. Figure 4 (left) shows comparison of hydrodynamic results of mean  $p_T$  with experimental data. It should be noted that HIJING, in which there is no rescatterings, cannot reproduce this mass splitting pattern. In Fig. 4 (right), ALICE  $v_2(p_T)$  data are compared with hydrodynamic results and this hydrodynamic model reasonably describes the tendency of the data.

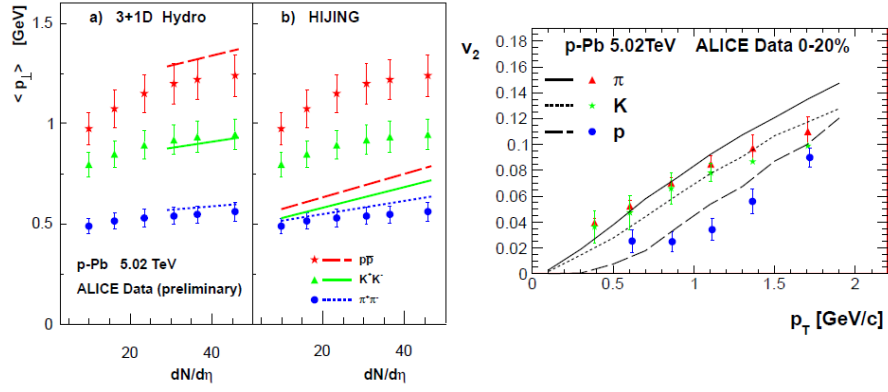


Figure 4: Mean transverse momentum as a function of charged particle multiplicity (left) and differential elliptic flow parameter (right) for particle identified hadrons in p+Pb collisions at 5.02 TeV [20].

On the other hand, the color reconnection option in PYTHIA is discussed by Ortiz and is found to result in apparent flow-like effect in particle ratio as a function of  $p_T$  [21]. It would be interesting to see in this calculation whether the ridge-like structure also appears in high-multiplicity p-p events.

One of the hydrodynamic results which I found intriguing in the conference [1] is shock-wave pattern in d-A collisions shown by Schenke. Figure 5 shows time evolution of energy density in d-Au collisions at the RHIC energy. This reminds us a volcano scenario by T.D. Lee [22]. “Squeeze-out” of matter can take place and substantial back-to-back correlation may appear perpendicular

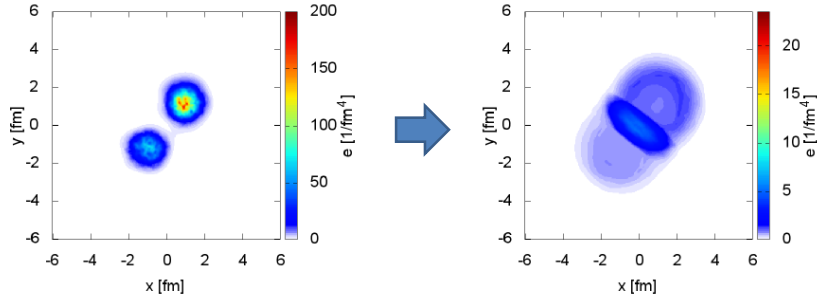


Figure 5: Time evolution of energy density in d-Au collisions at the RHIC energy. (Left) Initial condition at  $\tau = 0.2$  fm/c. (Right) Energy density distribution at  $\tau = 5.2$  fm/c. Figure is adapted from a talk by Schenke in this conference [1].

to the axis of the two nucleons in the deuteron. In this context, see also the pioneering work of hydrodynamic simulations with bumpy initial conditions from HIJING in A-A collisions [23].

In any case, the good news is that the physics of high-energy nuclear collisions has been more sophisticated. Before RHIC started, most of the people in this community did not believe hydrodynamic description of the QGP. Just after RHIC launched, hydrodynamic description immediately turned out to be successful. At that time, smooth initial conditions were employed, which means that the size of coarse-graining was of the order of 5 fm. In the last few years, event-by-event initial fluctuation gets important to understand higher order anisotropy. The size of the fluctuation or, in turn, the size of the coarse-graining is of the order of 1 fm or less. Obviously, resolution to describe initial profile is getting better. Now there is a possibility for hydrodynamic framework to work even in smaller system created in p-p or p/d-A collisions.

### 3. Isotropization and thermalization

Most of the people in this community agree that a final piece of jig-saw puzzle to solve high-energy nuclear collisions is to understand how to thermalize the system just after collisions. At leading order of CGC formalism, energy

momentum tensor just after the first contact of nuclear collision becomes [24]

$$T^{\mu\nu}(\tau = 0^+) = \text{diag}(\epsilon_0, \epsilon_0, \epsilon_0, -\epsilon_0), \quad (1)$$

$$\epsilon_0 = \epsilon(\tau = 0^+), \quad (2)$$

where  $\epsilon$  is the energy density of the color fields. Note that this energy momentum tensor is traceless due to scale invariance. A remarkable feature is that negative pressure appear in the longitudinal direction. This is something like an elastic body: Negative  $pdV$  work stores the system with energy through expansion of the system. The question in high-energy nuclear collisions is how to obtain the form of energy momentum tensor like

$$T^{\mu\nu}(\tau_{\text{iso/therm}}) = \text{diag}(\epsilon(\tau_{\text{iso/therm}}), P_T, P_T, P_L), \quad (3)$$

where  $P_T \approx P_L$  and isotropization or thermalization time  $\tau_{\text{iso/therm}}$  is of the order of 1 fm/ $c$ .

Temporal behavior of transverse and longitudinal pressure is discussed by Epelbaum. Classical Yang-Mills equation with the CGC initial conditions is solved in an expanding coordinate [25]. Figure 6 shows that  $P_L \sim 0.7P_T$  at  $\sim 0.4$  fm/ $c$  and that the system exhibits hydrodynamic behavior even for small coupling  $\alpha_s \sim 10^{-2}$ .

Anisotropic hydrodynamics helps us to describe this stage before conventional hydrodynamic regime in which isotropic pressure is required. Details of the formalism and its consequences were discussed by Strickland in this conference [26].

#### 4. Fluctuation

Topics of fluctuation in a broad sense are popular for these years. In this section, I discuss some aspects of fluctuation in high-energy nuclear collisions.

Relation between initial fluctuation of matter profile and final higher harmonics is the key to investigate transport property of the system. Figure 7 shows strength of correlation between initial eccentricity  $\varepsilon_2$  and final elliptic

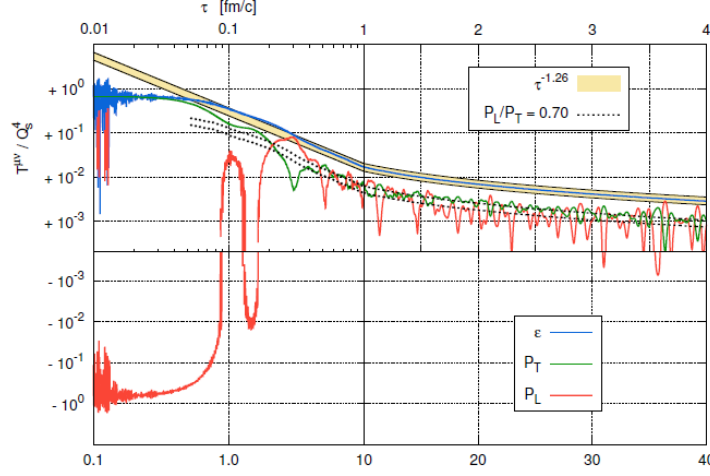


Figure 6: Time evolution of longitudinal (red) and transverse (blue) pressure in an expanding coordinate. This figure is adapted from a talk by T. Epelbaum in the conference [1].

flow parameter  $v_2$  in viscous hydrodynamic calculations with the ratio of shear viscosity to entropy density being  $\eta/s = 0.16$  [27]. As is shown, final elliptic flow parameter is strongly correlated with initial eccentricity. Regarding this, it would be interesting to see what happens to this correlation if hydrodynamic fluctuation during evolution is taken into account as discussed by Murase. Constitutive equation in general can be written as a stochastic equation,

$$\Pi(x) = \int d^4x' G_R(x, x') F(x') + \delta\Pi, \quad (4)$$

$$\langle \delta\Pi(x) \Pi(x') \rangle = TG^*(x, x'). \quad (5)$$

Here  $\Pi$  is the dissipative current,  $G_R$  is the retarded Green function ( $G^*$  being its symmetrized version with respect to time),  $F$  is the thermodynamic force and  $\delta\Pi$  is the hydrodynamic fluctuation as a random force. This is nothing but a fluctuation-dissipation relation. When dissipation exists, fluctuation should appear in a consistent manner [28]. These new sources of the fluctuation together with dissipative corrections will be implemented in next-generation hydrodynamic simulations.

Retinskaya discussed an inverse problem by assuming the following equation



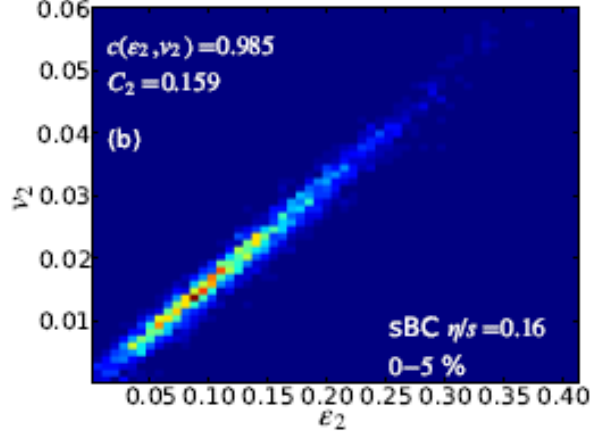


Figure 7: Correlation between initial eccentricity  $\varepsilon_2$  and final elliptic flow parameter  $v_2$  from event-by-event viscous hydrodynamic simulations. This figure is adapted from a talk by H. Niemi [1].

[29]:

$$v_n(\text{exp.data}) = \left( \frac{v_n}{\varepsilon_n} \right)_{\text{hydro}} \varepsilon_n. \quad (6)$$

One can estimate  $v_n/\varepsilon_n$  for a broad range of  $\varepsilon_n$  using viscous hydrodynamic simulations like Fig. 7. Within these model calculations, one can map experimental  $v_n$  data into higher order eccentricity  $\varepsilon_n$  from Eq. (6). Thus a reasonable scaling relation  $\varepsilon_2/\varepsilon_3^k = \text{const.}$  is found with  $k \sim 0.5$  for RHIC data and  $k \sim 0.6$  for LHC data. This result is obtained rather in a model-independent way in the initial stage. So one can test whether one's favorite model for initial conditions would obey this scaling relation. If not, the model could be discarded without performing massive hydrodynamic simulations. For a detail of comparison among initial models, see Ref. [29].

Conventionally hydrodynamic description is applicable when the spatial gradients of thermodynamic variables are small enough. This is one of the main reasons why hydrodynamic description would not be trusted in small system such as p-p or p-A collisions. Suppose that interaction region is large enough for hydrodynamics to be applied even in p-p collisions due to fluctuation of in-

elastic cross section. This is an idea of “fat” proton advocated by Muller [30]. If the deposited energy is sufficient for thermalization and the gradients of thermodynamic variables is small enough, there would be a chance for hydrodynamics to be applicable even in p-p collisions.

Fluctuation of saturation scale results in fluctuation of multiplicity. In particular, high multiplicity p-p events can be reproduced by IP-Sat model with fluctuating saturation scale [31]. Before going to A-A collisions, it is of particular importance to understand mechanism of particle production in rather simpler system such as p-p collisions.

## 5. Recent development in hydrodynamics and transport theory

One of the good news is a revival of the final state saturation model discussed by Paatelainen. This model is based on perturbative QCD parton production, saturation of gluons in the pre-thermalization stage and subsequent hydrodynamic evolution in (2+1)-dimensional space [32]. Just after RHIC started, one of the main observables was centrality dependence of multiplicity,  $(dN_{\text{ch}}/d\eta)/(N_{\text{part}}/2)$ . Several model predictions were compared with the RHIC data and, in fact, the final state saturation model [33] did not do a good job in this game [34]. However, there was a misidentification of centrality between theoretical results with experimental data [35]. After correcting this, results from the final state saturation model agree well with experimental data now.

Nowadays there are quite a lot of hydrodynamic simulations in the market. Dissipative effects are taken into account in most of the models directly by solving viscous hydrodynamic equations and/or indirectly by combining hydrodynamic simulation with subsequent kinetic evolution of hadron gases. In this conference, we saw two brand-new viscous hydrodynamic results from v-USPhydro [36] which is a successor of NeXSPheRIO and ECHO-QGP (Eulerian Conservative High-Order Code) [37]. The main focus of v-USPhydro is on the effect of bulk viscosity which has not been extensively discussed earlier. Although ECHO was originally developed for astrophysics, it is now applied to

the physics of QGP. Numerical tests are almost finished and now they are going to analyze actual data using this code.

Denicol investigated the effect of non-linear terms with respect to dissipative currents in the second order hydrodynamics equations [38] which have been missing so far in most of viscous hydrodynamic simulations. As expected, the difference between with and without non-linear term is manifested at large  $\eta/s > 0.2$ . In the viscous hydro code in the next generation, these non-linear terms should be taken into account.

Usually, it is almost impossible to incorporate critical behavior of phase transition in kinetic theory. This is the reason why hydrodynamics has an advantage against the kinetic theory. In these years, there is a trend that some of the hydrodynamic properties are implemented in the kinetic approaches. Marty discussed Nambu–Jona-Lasinio type phase transition in a kinetic theory [39] is combined with the framework of PHSD (Parton-Hadron String Dynamics) [40]. Greco implemented a fixed  $\eta/s$  in a transport model and analyzed flow data [41] to conclude evidence of phase transition.

## 6. Summary

p/d-A collisions provide us with a new opportunity to learn novel aspects of high energy hadron/nuclear reaction in a unified picture. It is good to keep in touch with each other between sub-communities of initial stages (CGC, nuclear PDF, etc.) and final evolution (hydro, transport, etc.). Future e-A program should shed light on more precise structure of hadrons/nuclei at very high energy.

## Acknowledgment

I would like to thank C. Salgado, N. Armesto, C. Pajares and other local organizers for excellent organization and, in particular, for providing us with a wonderful setting of fruitful discussion in this conference.

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